NSLS VUV RING LIFETIME STUDY*

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Abstract

A series of beam studies was recently done at NSLS VUV ring to better understand the beam lifetime. Lifetime is dominated by Touschek effect, and both beam measurements and simulations show that the dispersion and small physical aperture limits the survival of the particles in the Touschek scattering. The lifetime is significantly limited by large β_x at injection septum.

INTRODUCTION

Understanding and increasing beam lifetime is important as it provides more integrated flux for the users as well as reduces radiation exposure. Lifetime in the VUV ring has never been fully understood, measured lifetime is much shorter than earlier calculations.

The beam lifetime for a electron storage ring is usually limited by gas scattering or Touschek scattering. A series of studies was done recently on VUV ring to understand what is the dominating effect. Both beam measurement and simulation show that it is large dispersion and small physical aperture limiting the survival of scattered particles.

The NSLS VUV Ring has a nominal energy of 800 MeV, 4 cell DBA lattice, and 51 m circumference. The maximum current for a regular operation is 1 A. Top-off injection is applied every 4-5 hours. Machine parameters are listed in Table. 1.

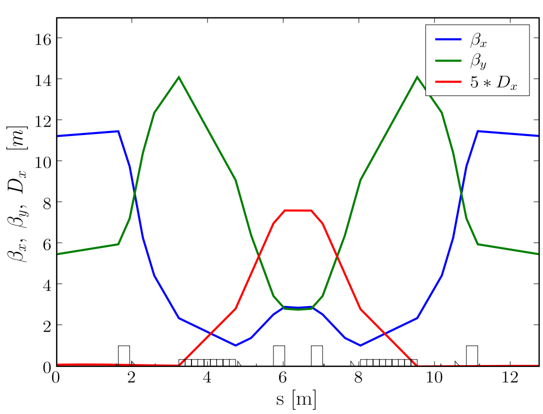

Figure 1: VUV Ring Lattice

Table 1: VUV Ring Parameters

Circumference	51.017 [m]
Momentum Compaction α_c	0.0235
RF Frequency	52.887 [MHz]
RF Peak Voltage	80 [kV]
Tune, ν_x,ν_y,ν_s	3.14, 1.26, 0.0018
Natural Energy Spread,σ_E/E	4.86×10^{-4}
Typical Bunch Mode(RF Buckets)	7(9)
Damped Emittance, ϵ_x/ϵ_y	160/4 nm-rad
β_x,max,min,average	11.4,1.0,5.3 [m]
β_y,max,min,average	14.1,2.8,8.1 [m]
Dispersion D_x, max	1.5 [m]

TOUSCHEK LIFETIME

Total beam lifetime usually consists of two parts, scattering from residual gas and scattering within the beam. The gas scattering lifetime is comprised of the elastic and inelastic scattering on electrons and nuclei, while the self-scattering within a beam is called Touschek effect.

Estimating gas scattering lifetimes based on measured pressures in the VUV ring vacuum chamber, we end up with values much longer than observed. Additionally at the same current per bunch, lifetime is independent of the fill pattern. These both argue that gas scattering is negligible for the VUV ring. Therefore in the rest of the paper we concentrate on Touschek lifetime.

Touschek lifetime comes from the effect that scattering of two particles in their center of mass frame transfers transverse momentum into longitudinal momentum. Particle loss happens when the longitudinal momentum exceeds the maximum acceptable momentum deviation[3]. This momentum acceptance may come from dynamic or physical aperture, or the RF bucket height, whichever is the smallest. Touschek lifetime describing this process is[2, 4]:

$$\frac{1}{\tau_t} = -\frac{1}{N_b}\frac{dN_b}{dt} = \frac{r_c^2 c N_b}{8\pi\sigma_x\sigma_y\sigma_\ell(\hat{\Delta p}/p)^3\gamma^2}C(\zeta) \qquad (1)$$

where

$$C(\zeta) \equiv \sqrt{\zeta}\Big(-\frac{3}{2}e^{-\zeta} + \frac{\zeta}{2}\int_\zeta^\infty \frac{\ln u}{u}e^{-u}\,du + \frac{3\zeta - \zeta\ln\zeta + 2}{2}\int_\zeta^\infty \frac{e^{-u}}{u}\,du\Big)$$

and $\zeta = \left(\frac{\beta_x}{\gamma\sigma_x}(\frac{\hat{\Delta p}}{p})\right)^2$, which depends on betatron amplitude function β_x, beam energy γ, and momentum accep-

* Work supported by grants from NSF PHY-0552389 and DOE DE-AC02-98CH10886
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tance $\hat{\Delta p}/p$ at the point of scatter. The momentum acceptance can be defined by mechanical aperture, dynamic aperture and RF bucket height. We will discuss it later. Touschek lifetime comes from an average of Eq. (1) over the whole ring.

For an equilibrium state of electron storage ring, where the required energy gain for acceleration or compensation of synchrotron radiation losses is U_0 per turn, the RF bucket height is[3]

$$\hat{\Delta E}/E_{\rm rf} = \left(\frac{2eV}{\pi\beta^2 Eh|\eta|}\right)^{\frac{1}{2}} Y(\phi_s) \qquad (2)$$

where E is beam energy, $\beta \approx 1$ for electron ring, h is harmonic number, η is phase slip factor and ϕ_s is phase of synchronous particle. The bucket height factor is $Y(\phi_s) = |\cos\phi_s - \frac{\pi - 2\phi_s}{2}\sin\phi_s|^{1/2}$. If there are other effects that limit the momentum acceptance, the tolerable momentum spread will be smaller than that in Eq. (2). i.e. $\hat{\Delta p}/p < \hat{\Delta E}/E_{\rm rf}$, we may have a shorter Touschek lifetime, and this is indeed the case for NSLS VUV ring.

From the discussion above, Touschek lifetime depends on the following parameters:

- Single bunch current.
- Beam volume, larger σ_x, σ_z and σ_ℓ will reduce the probability of scattering, and the lifetime is inversely proportional to the bunch density.
- Energy, which is hidden in emittance ϵ_x, RF acceptance in $C(\zeta)$, and bunch length σ_ℓ.
- Momentum acceptance is the smaller of physical aperture or RF bucket.

Based on these aspects, we did our experiments to understand Touschek lifetime in VUV ring.

Bunch Length Measurement

A photo diode used for bunch length measurement has a pulse response. The bunchlength is calculated from the measurement by:

$$\sigma_{\rm obs}^2 - \sigma_{\rm ls}^2 = \sigma_\ell^2 \qquad (3)$$

where $\sigma_{\rm obs}$ is the observed bunch-length, $\sigma_{\rm ls}$ is the diode-scope system pulse response, and σ_ℓ is the beam bunch-length.

The bunch length for a synchrotron is described by

$$\sigma_\ell = \frac{c|\eta|}{\omega_s}\frac{\sigma_E}{E} = \sqrt{\frac{2\pi\alpha hc^2}{\omega_{rf}^2\cos\phi_s}\frac{E}{eV_{rf}}}\sigma_E \qquad (4)$$

and the resolution term $\sigma_{\rm ls}$ can be regarded as constant.

Since $\sigma_\ell\omega_s = c|\eta|\sigma_E/E$ is only a property of lattice, i.e. a constant when changing the RF voltage. We can fit for $\sigma_{\rm ls}$ by measuring ω_s and fitting the $\sigma_{\rm obs}$ using Eq. (3). The RF voltage and power are related by fixed shunt impedance, R_s, therefore we can discuss the bunchlength and lifetime on RF power in stead of voltage. The result is shown in Fig.2 and has been also confirmed by streak camera data.

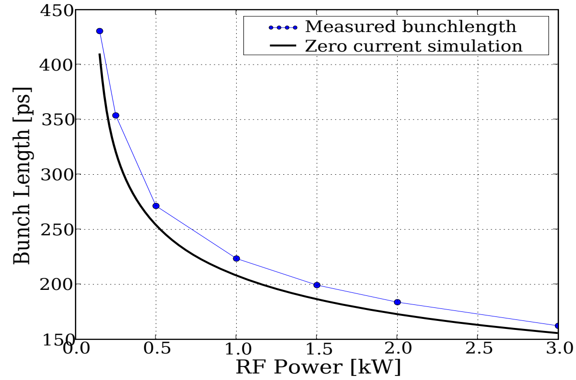

Figure 2: RMS Bunch Length. Single bunch operation at $I = 5mA$

Momentum Acceptance

Momentum acceptance $\hat{\Delta p}/p$ is the key parameter for Touschek lifetime, and it defines the maximum momentum deviation a particle can have.

The closed orbit for a off-momentum particle depends on a product of its momentum deviation δ and dispersion $D_x(s)$. At the center of dispersive region, after a Touschek scattering with energy change δ, the closed orbit of the reference particle will change from 0 to $D_x(s)\delta$, and execute a larger betatron oscillation along its new closed orbit. The physical coordinate of the betatron oscillation depends on the betatron amplitude and β_x, therefore the particle may get lost at large β_x locations, e.g. the straight section of VUV ring. An estimation of transverse momentum acceptance can be done based on lattice functions in Fig. 1. The beam pipe dimension is $\pm40\times\pm20$ mm, and maximum dispersion is $D_x \approx 1.5$ m. Touschek scattering may change the closed orbit and bring betatron oscillation with amplitude $D_x\delta$ at scatter s_0, and the amplitude at straight section with larger β_x should be $\sqrt{\frac{\beta_x(s)}{\beta_x(s_0)}}D_x\delta$. This should be less than half horizontal aperture, ±40 mm. For VUV ring, the septum is about 1 m long with an aperture about $\pm35 \times \pm20$ mm. $\beta_x(s) \approx 12$ m, $\beta_x(s_0) \approx 2.8$ m, and $D_x \approx 1.5$ m. Therefore the maximum momentum deviation is limited by the transverse aperture at other points of the ring to $\Delta p/p(s_0) \approx 1\%$.

To find the momentum aperture along the whole ring par ticle tracking was used. A module has been implemented in Elegant[1] to find the transverse momentum acceptance at each location along the ring, and the result for VUV ring is shown in Fig. 3. The straight line is the RF bucket height which dominates the momentum acceptance in the nondispersive region, while in the dispersive region the transverse momentum acceptance is dominating.

Effect of Physical Aperture

We believe the momentum acceptance is also limited by the ±35 mm physical aperture near injection septum and

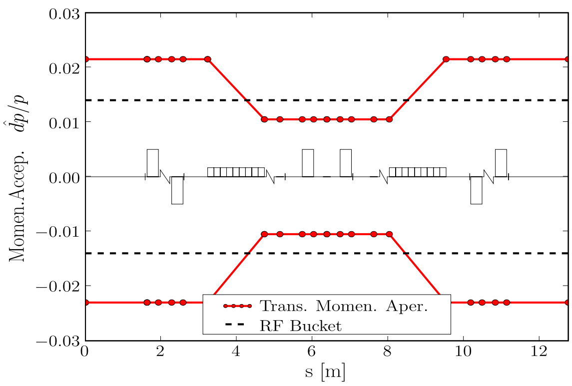

Figure 3: Momentum aperture.

the dispersion $D_x \approx 1.5$ m at the center of DBA cell. An experiment was done to study this effect, in which orbit was bumped locally in injection region, while kept unchanged at other locations. Fig. 4 shows that the lifetime is very sensitive to both sides of chamber wall. A significant lifetime drop happens when the beam is moved close to or away from septum, where we have small physical aperture. Currently the beam near the septum is locally centered (-8 mm) away from the global reference orbit. This centers the closed orbit between the septum and inner chamber apertures. The sharper dependence at negative values comes from a nonlinearity of the BPM and a longer aperture of the inner wall versus the shorter longitudinal aperture of the septum.

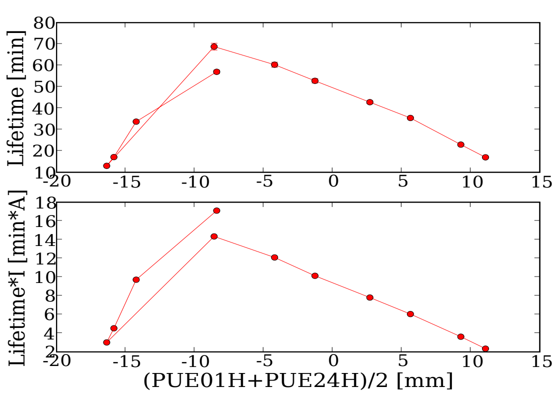

Figure 4: Lifetime variation with closed orbit locally bumped near injection septum.

A program provided by Elegant[1] was used to calculate Touschek lifetime for the VUV ring model with lattice shown in Fig. 1 and momentum aperture in Fig. 3. The resulting lifetime times current as a function of RF power is shown in Fig. 5. A break point exists around 1.2 kW, and separates the lifetime into two regions dominated by different effects. Above 1.2 kW, increasing RF voltage only improve the overall momentum acceptance slightly, since almost half of the ring is dominated by a smaller transverse momentum acceptance. Below 1.2 kW, it is always RF dominated, and lifetime become more sensitive to RF bucket height. The simulation disagrees with the measurement indicating a possibly smaller physical aperture exists than the designed ± 35 mm aperture. This is shown for several smaller values of aperture down to ± 25 mm.

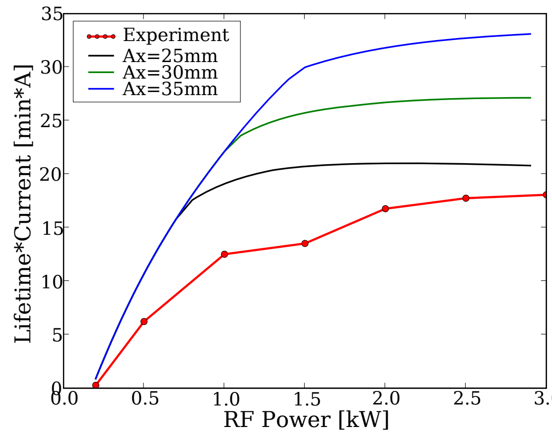

Figure 5: Touschek lifetime simulation and experiment. Single bunch operation, ≈ 130 mA

CONCLUSION

We have done both experiments and simulations to understand the lifetime of VUV ring. Gas scattering has very weak effect, while Touschek scattering dominates in VUV ring beam lifetime. The large dispersion and small physical aperture near injection septum accounts for the essential limitation on momentum acceptance, therefore higher RF voltage won't improve a lot in beam lifetime, but below 1.2 kW may bring down the lifetime quickly. The difference between simulation and experiments show the lifetime is smaller than can be explained by the known apertures in the ring. Further studies will be needed to identify its source.

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